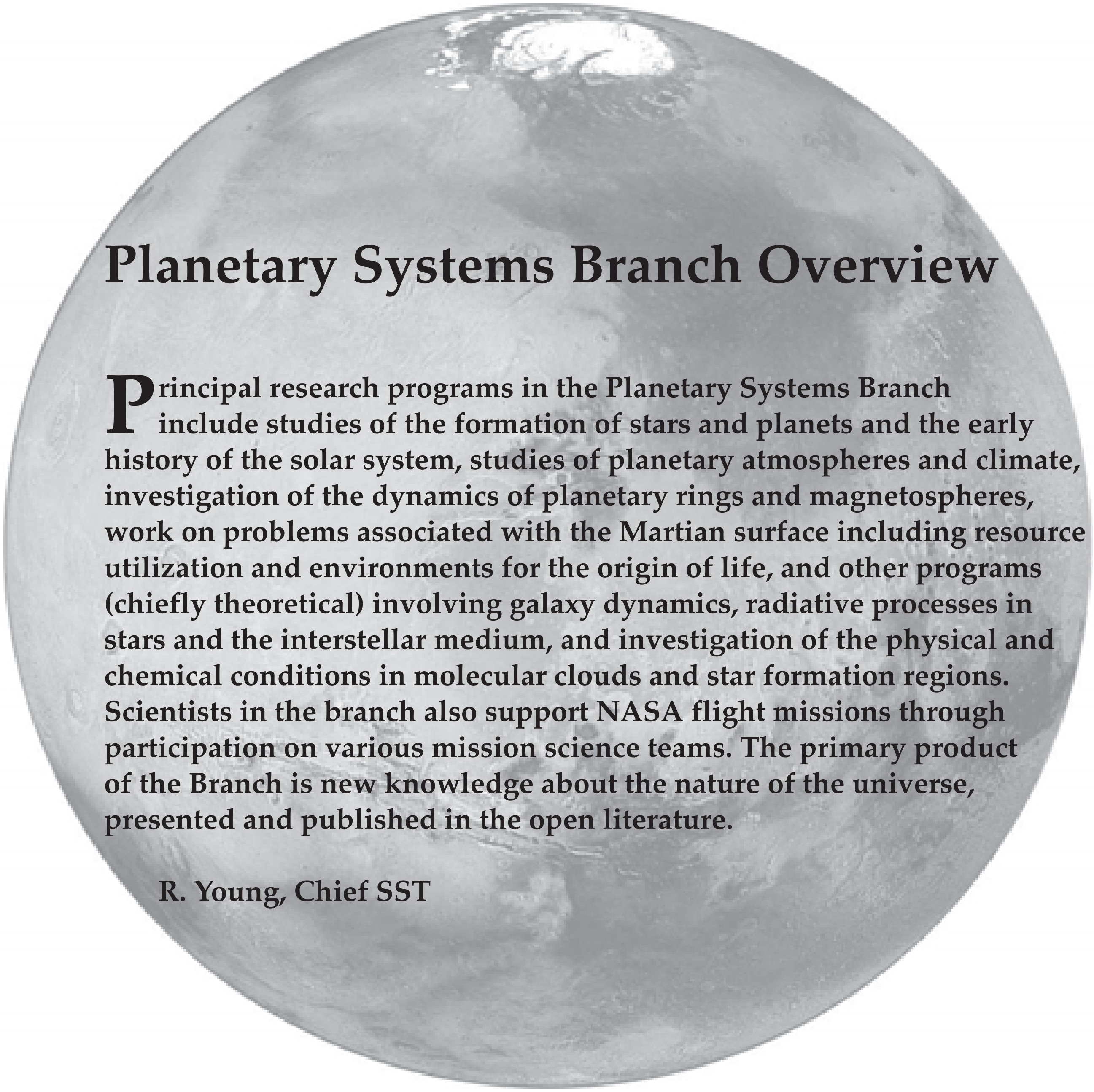

Planetary Systems Branch Overview

Principal research programs in the Planetary Systems Branch include studies of the formation of stars and planets and the early history of the solar system, studies of planetary atmospheres and climate, investigation of the dynamics of planetary rings and magnetospheres, work on problems associated with the Martian surface including resource utilization and environments for the origin of life, and other programs (chiefly theoretical) involving galaxy dynamics, radiative processes in stars and the interstellar medium, and investigation of the physical and chemical conditions in molecular clouds and star formation regions. Scientists in the branch also support NASA flight missions through participation on various mission science teams. The primary product of the Branch is new knowledge about the nature of the universe, presented and published in the open literature.

R. Young, Chief SST

Meteorites and Solar Nebula Analogs

P.M. Cassen and K.R. Bell

The planets in our solar system formed from a gaseous disk known as the solar nebula. Analogous nebulae are now commonly being observed in other solar systems by facilities such as the Hubble Space Telescope (HST) and the Infrared Astronomical Observatory (IRAS). Learning about these 'external' systems provides insight into the processes which led to the formation of our own life-supporting planetary system.

Stars typically form in dense stellar aggregates. In some clusters of young stars such as the Orion nebula, radiation from high mass stars disperses nebular material from nearby low mass systems (this process is discussed more fully in the Hollenbach *et al*. report). In many systems however, flattened nebulae, with mass sufficient to form planets similar to those found in our own solar system, survive for millions of years after the coalescence of the central star. The temperatures and densities at the midplanes of these 'protoplanetary disks' determine the characteristics of the planetary systems which ultimately arise out of the disks as well as the elemental and isotopic compositions of the meteoritic material that survived from that era. P.M. Cassen and K.R. Bell are pursuing studies of the pre-planetary evolution of solar nebula by studying analogs in external systems and the evidence in our own meteoritic record.

Until recently, purely theoretical considerations were the main source of information regarding the thermal evolution of protoplanetary disks. P. Cassen and D.S. Woolum (California State University at Fullerton) examined astronomical data regarding the photospheric temperatures of disks around T Tauri stars (young solar mass stars), as constrained by observations at optical, infrared, and radio wavelengths. They developed theoretical models to use these observations to infer the internal thermal structure of the disks. The models account for obscuring circumstellar matter, dust high in the nebular atmosphere, and the optically thick nature of the disks themselves. They found that most disks in the planet-forming stages were quite cool (at temperatures permitting the condensation of water or ice in what would correspond to the terrestrial planet region), but that disks were likely to be very hot early in their evolution, when they are still heavily obscured by in-falling material. In the latter cases, the total system luminosity provides an estimate of accretional energy. Comparisons with revealed T Tauri luminosities provide a basis for estimating the properties of embedded disks. High temperatures at early stages would explain a variety of properties characteristic of the primitive meteorites.

Evidence for nebular temperatures as deduced from meteorite properties was explored in more detail in collaborative research between K.R. Bell, P.M. Cassen, J.T. Wasson (Institute of Geophysics and Planetary Physics, UCLA), and D.S. Woolum. Patterns of elemental and isotopic abundances in meteorite components indicates that they formed in a nebula with temperatures ranging from 1400 K (above the destruction temperature of most solids such as silicates) to 400 K (a temperature low enough to permit the incorporation of water into rocky material). This wide range suggests that meteorite components were formed over an extended time during the cooling of the solar nebula. Midplane temperatures of optically visible T Tauri disks fall at the cool end of this temperature range. Using the assumption that our solar system underwent thermal evolution typical for systems with similar stellar mass, Bell et al. argued that T Tauri systems are nearing the end of their meteorite formation phases. Further, T Tauri systems must at one point have experienced a hotter, more active phase of disk evolution. This earlier phase presumably occurred while the system was still optically obscured (well embedded in the disk) and is therefore associated with the high accretion rate, protostellar phase. ❑

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Primary Accretion in the Protoplanetary Nebula

J.N. Cuzzi, R.C. Hogan, J.M. Paque, and A.R. Dobrovolskis

The ‘primary accretion’ of comets and asteroids is not understood. Yet, these so-called ‘primitive’ objects represent the parent bodies for the entire meteorite record – a vast data set that has little context for interpretation. The focus of this work is on 3D direct numerical simulations of particles in turbulence; aerodynamically-selected particles are concentrated in turbulence by a factor which can be up to a million in the nebula. Optimally selected particles have a Stokes number of unity, where the Stokes number is the ratio of particle stopping time to the Kolmogorov eddy turnover time, and is proportional to the particle radius and density. The simulation code handles Reynolds number (Re) as high as 1300, and 10^6 particles at each of 16 Stokes numbers simultaneously.

Recent results show that the shape of the turbulent concentration (TC) function is independent of both turbulent intensity (Re) and the concentration factor (in the high concentration limit appropriate for the nebula). The predictions are well-fit by a lognormal function. Also, a so-called ‘unequilibrated ordinary chondrite’ ALH 85033 was 'disaggregated' and the size distribution of the chondrules was measured directly. These data are far superior to similar data obtained by examining slices of rock in a microscope; they provide direct determination of the chondrule density, which cannot be attained any other way. Previous research merely measured particle radius and assumed an average density for all particles. The new data change the shape of the distribution curve for concentration.

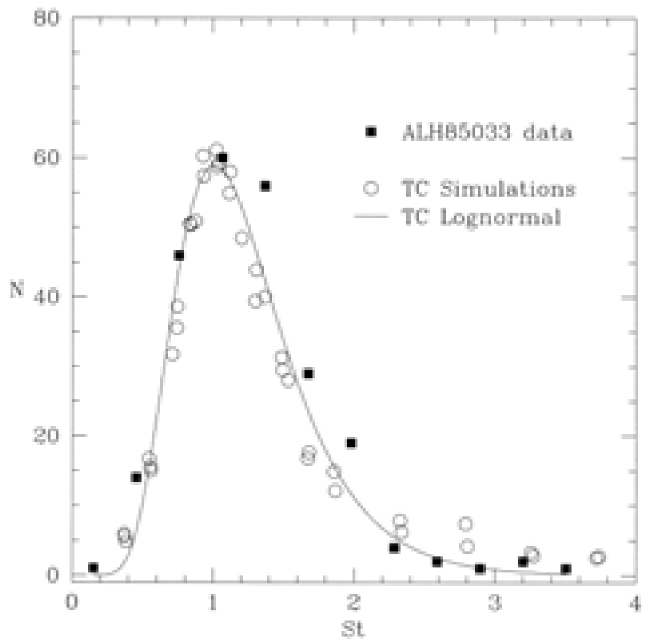

Figure 6. Comparison of model predictions with the actual relative abundance of chondrules, as a function of the product of particle radius and density.

Figure 6 compares model predictions with the actual relative abundance of chondrules, as a function of the product of particle radius and density. The open circles are the predictions, for all three Re values we simulated – there is no significant Re dependence of the shape.

The solid curve is the best fit of a lognormal function to the actual simulations. The filled squares are the meteorite data. The data and the predictions are normalized together at their peaks, and the shapes agree very well without any free parameters in the theory. The so-called Weibull function previously assumed (also shown) is based not on aerodynamic sorting but on fracture processes, and has several free parameters.

The theory was also generalized to other particle properties and nebula locations. Not all particles in the nebula are likely to be solid silicates. The earliest condensate grains probably stick into fluffy 'fractal puffballs' and then porous aggregates which have lower average density. These particles will incur preferential concentration in areas of the nebula where the gas density is commensurately lower, such as the formation regions of the gas giants and comets.

Figure 7 shows the expected particle radius-density product amenable to preferential concentration as a function of turbulent intensity (the latter expressed as scaling parameter alpha). Current estimates for nebula alpha are in the range from 10^{-4} to 10^{-2}. Thus, while solid chondrules (CH) are concentrated in the terrestrial planet region (1-2.2 AU, or astronomical units, where 1 AU is the earth's distance from the sun), porous aggregates (PA) are concentrated at the same level of turbulence in the lower density regions at the locations of Jupiter, Saturn, and Uranus (5, 10, and 20 AU). Low gas density is also found at large heights above the nebula midplane even at 1-2 AU. The most fluffy aggregates (FA) are concentrated at extremely low density and/or high turbulent intensity. ❑

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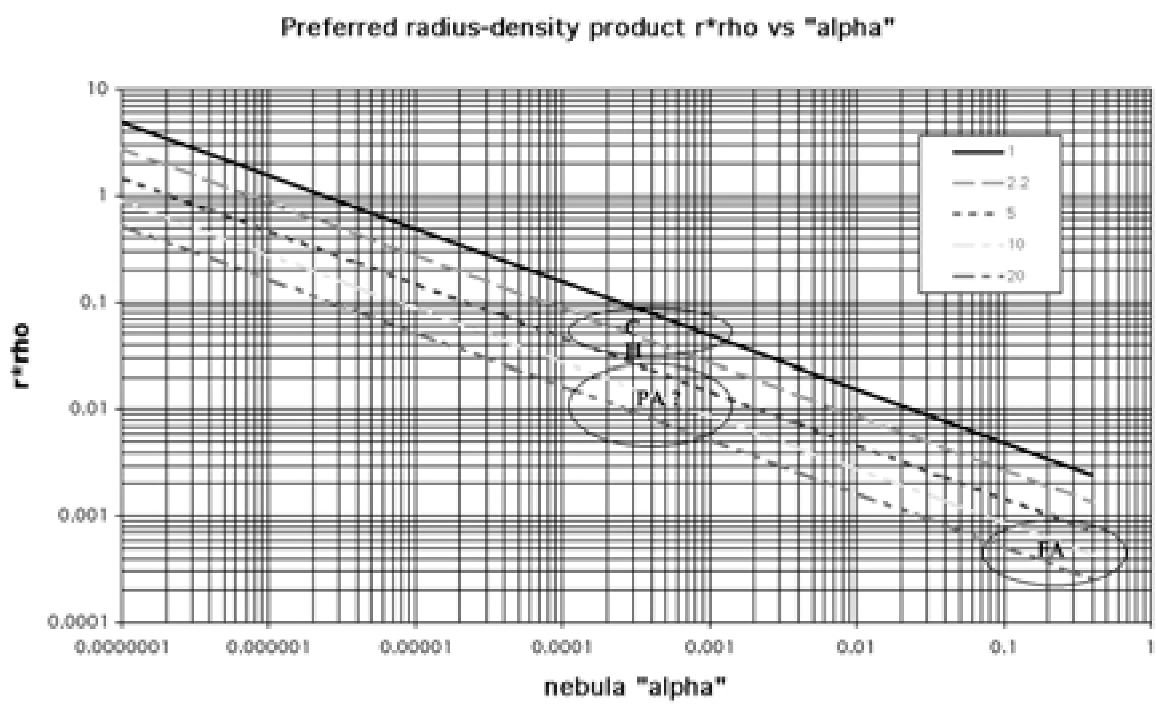

Figure 7. The expected particle redius density product amenable to preferential concentration as a function of turbulent intensity.

The Center For Star Formation Studies

D. Hollenbach, K.R. Bell, and P. Cassen

The Center for Star Formation Studies, a consortium of scientists from the Space Science Division at Ames and the Astronomy Departments of the University of California at Berkeley and Santa Cruz, conducts a coordinated program of theoretical research on star and planet formation. The Center, under the directorship of D. Hollenbach (NASA Ames), supports postdoctoral fellows, senior visitors, and students, meets regularly at Ames to exchange ideas and to present informal seminars on current research, hosts visits of outside scientists, and conducts a week-long workshop on selected aspects of star and planet formation each summer.

One focus of the NASA Ames portion of the research work in 1998 involved the dispersal of the protoplanetary disks which ultimately form planets. The formation of a planetary system includes a number of sequential stages. The collapse of a giant cloud of interstellar gas and dust results in a central protostar with a protoplanetary disk of orbiting gas and dust. The gas and dust spirals onto the star, causing the star to grow in mass, a process called 'viscous accretion.' At the same time, the dust in the disk settles to the midplane, and coagulates into large, ice/rock planetesimals. The collisions of these planetesimals leads to larger planets, and if the mass of the planet becomes greater than about 15 Earth-masses, the gravity of the planet can attract the gas in the disk, and the planet rapidly adds considerable more mass as it accretes gaseous hydrogen and helium. In this way, giant gaseous planets such as Jupiter are formed. During the same period, the wind from the central star 'blows' on the disk and carries gas and dust back out into the interstellar medium. In addition, the ultraviolet radiation from the central star, or from a nearby, luminous star, heats the surface of the disk to thousands of degrees in temperature, and the gas and dust is evaporated into the interstellar medium. Therefore, the gas and dust in a protoplanetary disk have four possible fates: accretion onto the star, accretion onto planets, wind-stripping, or photoevaporation. D. Hollenbach, H. Stoerzer, D. Johnstone (University of Toronto), and H. Yorke (Jet Propulsion Laboratory) studied the relative importance of these four disk dispersal mechanisms. They showed that winds are probably not significant, and that the photoevaporation and viscous accretion mechanisms compete with planet formation in dispersing the disk in a time scale on the order of one to ten million years. The outer disk is especially susceptible to photoevaporation, and this may explain why Uranus and Neptune have so much less gas mass than Jupiter and Saturn. Many planetary systems form in clusters which include massive, luminous stars. The ultraviolet radiation from these luminous stars can evaporate their own disks, and nearby disks circling lower mass stars, in time scales of order 100,000 to 1,000,000 years, perhaps preventing or truncating planet formation.

Disks observed around low mass young stars, which are not disrupted by nearby bright stars, are expected to give rise to planetary systems. Research by P.M. Cassen and D.S. Woolum (California State University at Fullerton) has led to a derivation of disk midplane conditions from observations of disk around young, low mass systems (see the Cassen and Bell report for more details on this research). They find that disks in the planet-forming stage are quite cool. They, along with K.R. Bell and J.T. Wasson (Institute of Geophysics and Planetary Physics, UCLA), argue from meteoritic abundance patterns that an earlier, hotter phase of nebular evolution must have existed. This phase is identified with embedded protostars.

The theoretical models developed by the Center have been used to interpret observational data from such NASA facilities as the Infrared Telescope Facility (IRTF), the Infrared Astronomical Observatory (IRAS), the Hubble Space Telescope (HST), and the Infrared Space Observatory (ISO, a European space telescope with NASA collaboration), as well as from numerous ground-based radio and optical telescopes. In addition, they have been used to determine requirements on future missions such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the proposed Space Infrared Telescope Facility (SIRTF). ❏

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Detection and Models of Extrasolar Planets

Jack J. Lissauer

The objectives of this project are to study planets around stars other than our own Sun both observationally and by developing theoretical models of the formation and stability of planets and planetary systems.

A team of astronomers from San Francisco State University, the Anglo-Australian Observatory, Lick Observatory, and Ames have discovered a planetary-mass companion orbiting the star Gliese 876. The newly found body has a mass multiplied by the sine of the inclination of its orbit normal to the line of sight of 1.9 times that of Jupiter, a period of 61 days (implying a semi-major axis of 0.2 AU) and an eccentricity of 0.37. The planet was identified using Doppler measurements of the radial velocity of the star at the Keck and Lick observatories. This planet is closer to the Sun than is any other extrasolar planet thus far identified. More significant is the fact that Gliese 876 is an M4 star with a mass about 1/3 that of our Sun. This is the first planet to be discovered in orbit about an M star, and as most stars in our galaxy are faint M stars like Gliese 876, its existence suggests that billions of planets probably are present within our galaxy.

A set of plausible outer planetary systems were constructed using direct numerical integrations by a team of astronomers from the Southwest Research Institute, Queen's University, and Ames. It was found that in order to construct planetary systems like our own, some sort of dissipation was required to continue during the accretionary epoch for time scales longer than 10 million years. The number of planets can vary from one to seven. Systems with a large number of planets never contain very massive, Jupiter-like planets, but instead are made up of Uranus-like planets. Stable planetary systems can include planets in mean motion resonances with one another. Perhaps most surprisingly, it is possible to construct stable systems in which planetary orbits can undergo large, semi-periodic changes.

Models of the growth of giant planets close to their stars were constructed by a group from Lick Observatory and Ames. If adequate solid planetesimals are available near stars, planetary cores can grow massive enough to accrete large amounts of gas from the protoplanetary disk. However, for conditions similar to those believed to have existed around our Sun, planetary growth several astronomical units from the star, followed by subsequent inward migration, appears to offer a more likely scenario. ❑

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1999 Marsokhod Rover Field Experiment

C. Stoker, N. Cabrol, T. Roush, J. Moersch, V. Gulick, G. Hovde, and the Marsokhod Rover Team*

A field experiment to simulate a rover mission to Mars was performed in Feb. 1999. This experiment, the latest in a series of rover field experiments, was designed to demonstrate and validate technologies, investigate strategies for high-science, high-technology performance, and define cost-effective planetary rover operations.

The experiment objectives were to: 1) train scientists in a mission configuration relevant to Mars Surveyor program rover missions at a terrestrial analog field site simulating the criteria of high-priority candidate landing-sites on Mars; 2) develop optimal exploration strategies; 3) evaluate the effectiveness of imaging and spectroscopy in addressing science objectives; 4) assess the value and limitation of descent imaging in supporting rover operations; and 5) evaluate the ability of a science team to correctly interpret the geology of the field site using rover observations.

A field site in the California Mojave Desert was chosen for its relevance to the criteria for landing site selection for the Mars Surveyor program. These criteria are: 1) evidence of past water activity; 2) presence of a mechanism to concentrate life; 3) presence of thermal energy sources; 4) evidence of rapid burial; and 5) excavation mechanisms that could expose traces of life.

The Marsokhod rover shown in figure 8 was used for the test. The Marsokhod chassis is an all-terrain vehicle developed as a flight

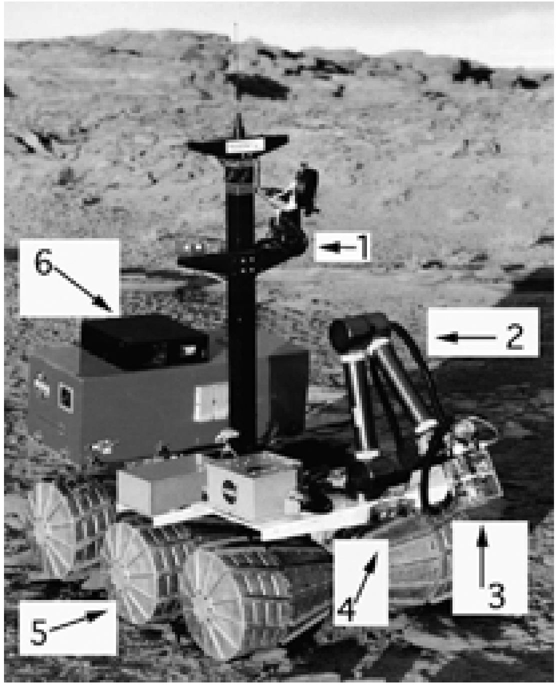

Figure 8. Marsokhod rover with: 1) mast carrying stereo color cameras, stereo navigation cameras and NIR spectrometer; 2) five DOF manipulator arm; 3) carousel end-effector; 4) front pallet navigation cameras; 5) titanium wheels; 6) onboard electronics and computer.

prototype by the Mobile Vehicle Engineering Institute (VNIITransmash) in Russia. The chassis is 100-cm wide, 50-cm long, and has a 35 kg unloaded mass. The chassis consists of three pairs of independently driven titanium wheels, joined together by a three degree-of-freedom (DOF) passively articulated frame. Two degrees-of-freedom allow the frame to twist, while the third allows it to pitch. The central mast carries a stereo imager consisting of two 3-chip color 640x480 pixel CCD cameras providing 0.30 mrad/pix resolution with a 25-centimeter stereo baseline at 178-cm height. Monochrome stereo CCD cameras with resolution of 0.9 mrad/pix are mounted on the mast and the front and rear pallets near the wheels. These cameras are used for navigation and arm placement.

The rover payload also includes a Near Infrared (NIR) fiber-optic spectrometer operating in the range from 0.35 to 2.5 micrometers. The 1 degree instrument field of view (IOFV, approx. 17 mrad) fore-optic of the spectrometer is bore-sighted with the color stereo mast camera. The files produced by the spectrometer are automatically interpolated by the data collection software from the nominal instrumental spectral resolution to a resolution of 0.001 micrometer over the entire spectral domain. Automated spectral analysis was performed onboard to search for the spectral signature of carbonate minerals. Finally, the Marsokhod was equipped with a 5 DOF manipulator arm and a carousel end-effector. A color camera mounted on the end-effector of the arm could resolve 0.08 mm/pixel at closest position. A clamshell scoop occupied another position in the carousel.

Some additional instruments were included as part of the simulated payload but were operated independently from Marsokhod. A set of simulated descent images were obtained using a helicopter flight over the landing site. The image resolutions and field of view were designed to simulate the Descent Imager camera selected for the 2001 Surveyor mission. A portable, battery-powered Fourier transform infrared (FTIR) spectroradiometer operating in the 8-14 µm wavelength range at a resolution of 6 cm^{-1} simulated the Thermal Emission Spectrometer selected for the Mars 2001 mission. A foreoptic gives an IFOV of 15 mrad (FWHM), or 15 cm at a range of 10 m. This spectrometer, mounted on a tripod, was pointed by a field assistant at targets specified by the science team. Finally, simulated arm camera images were obtained with an engineering model of the University of Arizona Robotic Arm Camera selected for flight on Surveyor Mars missions for 1998 and 2001. This instrument was mounted on a tripod and pointed by a field assistant upon commands from the science team. It was used to image the walls of a trench dug by a field assistant.

Twenty participating scientists, unfamiliar with the site, directed the rover science mission for two weeks in February 1999. Prior to the mission, the science team were provided with orbital images with resolutions comparable to Viking and MOC images, and with Landsat Thematic Mapper images to use for traverse planning and formulating a science strategy. Simulated descent images were provided to the science team at the outset of the rover operations. A portable satellite dish, set up at the field site, enabled communication between mission control at Ames Research Center and the rover in the field. Data volumes were restricted to 40 mbits per command cycle as expected for actual Mars Surveyor missions. During the primary phase of the mission (Feb. 8-10, 1999) a total of 3 communication cycles/day were used by the science team located at Ames. During the extended phase of the mission, 1-2 cycles/day were used and the science team, many of whom participated from their home institutions via a world-wide-web interface and teleconferences. The science team was asked to: 1) use the orbital and descent data to develop hypotheses that could be tested using rover data; 2) characterize and identify rocks representative of the main geological events at the landing site; 3) identify the main geologic processes that have operated on materials at the landing site using their mineralogy, surface texture, morphology, and context; 4) reconstruct the stratigraphic sequence of events at the landing site; 5) identify rocks and soils that have the highest chance of preserving ancient environmental conditions favorable to life; and 6) characterize and cache samples of rocks which may have preserved evidence of life. Science team interpretations were compared with ground truth as evaluated by a science team in the field.

* Marsokhod Rover team is the staff of NASA Ames Intellegent Mechanisms Group and other members of the Information Technology Division at NASA Ames Research Center. ❏

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Magnesium-Rich Pyroxene Crystals Discovered in Comet Hale-Bopp

Diane Wooden

Analysis of silicate features in comet Hale-Bopp led to the discovery of abundant magnesium (Mg)-rich pyroxene crystals in the coma. Hale-Bopps' pyroxene crystals are analogous to pyroxene Interplanetary Dust Particles (IDPs), which also may be of cometary origin. The Mg-rich pyroxene crystals represent either pristine solar nebula condensates or relic interstellar grains. If the Mg-rich pyroxene crystals are relic interstellar grains, their preponderance in cometary comae implies that the outer solar nebula, where icy planetesimals formed, received significant contributions of presolar materials. Interstellar relic grains in comets are probable sources of complex organic molecules. Such complex organic materials may have been delivered by comets to early Earth during the heavy bombardment period.

The Ames HIFOGS mid-IR spectrometer acquired 7.5-13.5 µm spectra of comet Hale-Bopp over a large range of heliocentric distances from July 1996 through August 1997. Silicate minerals produce Si–O vibration modes in this portion of the electromagnetic spectrum. Comet Hale-Bopp was observed over a large range of heliocentric distances (3.6 AU to 0.95 AU, and back out to 2.4 AU) and the silicate feature was discovered to change in shape as the comet approached the Sun, and revert to its previous shape upon recession from the Sun. From analysis of the temporal evolution of these mid-IR spectra, a cooler, Mg-rich crystalline silicate grain component – crystalline pyroxene (Mg, Fe) SiO_3 – was discovered in the comet. The pyroxene crystals are so Mg-rich that they absorb sunlight less efficiently, making them cooler than the other silicate mineral grains. These pyroxene crystals are about ten times more abundant than the other silicate grains, and have been previously spectroscopically undetected in comets. The preponderance of Mg-rich pyroxene crystals in comet Hale-Bopp agrees with the dominance of pyroxene IDPs and with the dominance of Mg-rich pyroxenes in the reanalysis of PUMA-1 flyby measurements of comet Halley. ❏

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Refugia from Asteroid Impacts on Early Mars and Earth

Kevin Zahnle and Norman H. Sleep

Impacts on planets by large comets and asteroids were relatively frequent events in the early solar system. These impacts posed a major recurrent hazard to the continuous existence of life on early Mars and Earth. The chief danger would have been presented by globally distributed ejecta. These ejecta included large sub-orbital projectiles, mountains of finely subdivided dust, and in the worse case thick transient rock vapor atmospheres. On the Earth, down-welling thermal radiation from the hot atmosphere boiled the surfaces of the oceans. Water evaporated until either the energy contained in the rock vapor atmosphere is exhausted or the oceans boiled off. The Earth's oceans thereby provided an enormous thermal buffer that limited thermal excursions triggered by very large impacts, provided that the impact was not too large. Life could have survived in deep cool waters or in deep subsurface 'hideouts' until the danger passed and the rock was returned to its desirable crustal status. But if an impact was truly enormous (>1028 Joules, or a 500-km-diameter impactor 'the size of Texas'), the oceans vaporized and it would take at least 3000 years, (the time required to recondense and rain out all the water of the oceans) for conditions to return to some semblance of their original state. Thermal conduction would carry the thermal pulse to some considerable depth, while upwelling geothermal heat (much more than experienced in modern times) would leave any habitable niches wedged 'between the firepan and the fire.' Under such conditions the survival of any life present on the Earth would be threatened.

The lack of deep oceans on Mars means that there is no thermal buffer against even relatively small impacts and so the effect is quite different. Even an impact as small as the K/T event (the Cretaceous/Tertiary asteroid that killed the dinosaurs and 95% of the other lifelines on the Earth) would raise the martian surface to the melting point. This would be bad for life at the surface (e.g., for photosynthesizers), but the melting would not be deep, and the effects would soon (i.e., in hours-to-days) be forgotten as the energy of the impact quickly radiates into space. Even for larger events, the effects, although briefly scalding, are mitigated on Mars. For example, the low martian escape velocity permits a fair fraction of the hottest and most energetic ejecta to escape entirely, and thus not contribute to hazards to the hypothetical biota. Instead, because the gravity is lower the global ejecta on Mars are relatively massive but relatively cool. Survival of subsurface ecosystems is more likely on Mars than on Earth because: 1) Mars' lower geothermal heat flow and lower gravity permit deeper colonies (it is gravity that crushes rocks and seals pores; lower gravity permits deeper circulation of fluids, etc.), and 2) The thermal pulse from a major impact is more brief, thus there is more space between the firepan and the fire.

The possibility that Mars may have provided a more survivable platform for life in the earliest solar system, coupled with the demonstrated fact that Earth at least can receive lightly shocked ejecta from Mars, brings us to consider briefly the implications of exchange of materials between the two worlds. Lightly shocked ejecta, launched by impact and possibly stocked by crews of inadvertent microbial spacefarers, could make the voyage between planets. It does seem possible, even likely, that viable organisms have been launched by impact on favorable trajectories from Earth to Mars, so that after a relatively brief and altogether survivable trip through interplanetary space the terrenes might have found suitable homes; and of course the story could be reversed, which would make us all, in a sense, martians. ❏

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Martian Oxidant Mixing by Impacts

Aaron P. Zent

It is the objective of this work to revise previously published profiles of the oxidative stratigraphy of the martian regolith to include the effects of regolith stirring by impact cratering. The fundamental objectives are to estimate the depth from which samples must be obtained in order to access martian organics, and to clarify the unknowns in the problem to help direct future research.

One of the fundamental operational objectives of NASA's Exobiology Program is to return and examine organic material from the martian regolith. This objective derives from observations of the martian surface that indicate liquid water played an as-yet-unexplained role in the evolution of the martian surface early in the planets history, the same period during which life is suspected to have made its first appearance on Earth. The chemical evolution that lead to terrestrial life might have occurred on Mars as well The opportunity to compare the paths of prebiotic chemical evolution on two planets is likely to illuminate fundamental principles that govern the abiotic origin of life.

The most salient barrier to this objective is that the martian regolith is highly oxidizing, thus destroying putative martian oxidants. The specific chemical mechanisms which are responsible for the oxidizing nature of the martian surface remain unknown, but the photochemistry of atmospheric water is thought to be the ultimate source of the oxidants). This hypothesis predicts that strong oxidants are present at the base of the martian atmosphere and diffuse into the martian regolith, where they can react with any organics that may be at depth. The depth to which the oxidants might diffuse is unknown, but the regolith sampled by Viking was found to be oxidized to 10 mm. Therefore, considerable effort is being expended to understand the adsorptive and diffusive properties of H_2O_2 through silicate materials, as well as their reaction and complexation pathways, so that the thickness of the oxidizing layer can be predicted. However, it may not be sufficient to understand the diffusion of a vapor phase oxidant into the martian regolith, because the martian stratigraphic column is not stable, and was even less so early in its history. Aeolian and impact mechanisms act to erode and deposit material across the martian surface, effectively stirring the surface materials.

It is possible to estimate quantitatively, the mixing of a near-surface oxidized layer into the martian subsurface by impact cratering. Impact craters leave a clear signature in a planetary surface. Mixing models can be constructed (see figure 9) based upon simplified geometric and probability assumptions, which will describe the movement of materials up into the oxidizing zone, and down again, in response to subsequent burial (this cycling of material is referred to as 'regolith gardening.')

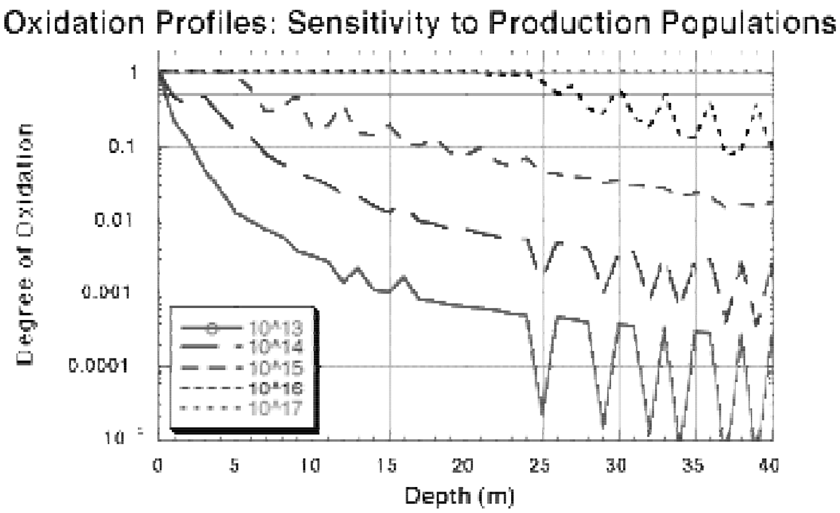

Figure 9. The sensitivity of the regolith oxidation profile to the pre-exponential factor in the production population is shown in this plot. Each increase in a factor of 10 in impact frequency considerably increases the depth from which samples must be acquired. The horizontal line represents a 50% likelihood of retrieving putative organics.

The effects of regolith gardening are quantitatively estimated, and combined with the effects of oxidation by atmospheric gases to produce estimates of the degree of oxidation of the martian surface with depth. We explore the effects of different crater production populations along with variations in H_2O_2 extinction depths, and hydrothermal oxidation of ejecta. In very select circumstances involving very early onset of oxidizing conditions during heavy bombardment, 150 to 200 m of regolith could be fully oxidized. More likely scenarios for the crater production population, onset of oxidizing conditions, and oxidant extinction depth yield estimates of no more than a few meters to putative reducing material. In addition, uncertainties remain regarding the degree to which hydrothermal or other high temperature chemistry might oxidize materials in ejecta blankets. The trade between accessing unlithified sediments or rock interiors must be considered. ❏

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